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Hadrons with charmed quarks in matter

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Abstract. We investigate the $D\bar{D}$ decay width of excited charmonium states at finite nuclear density with simultaneous modification of both D and $\bar{D}$ mesons in nuclear matter. The strongest effect is found for the Ψ' meson. The medium modification can be detected by dilepton spectroscopy as substantial Ψ' broadening and anomalous Ψ' absorption.

PACS. 13.25.Gv Decays of J/Ψ, Υ, and other quarkonia – 14.40.Lb Charmed mesons – 14.65.Dw Charmed quarks – 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes

1 Introduction.

In dense and hot nuclear matter the light quark condensates $q\bar{q}$ might be substantially reduced. This affects the light quark content of mesons and baryons and therefore results in medium modification of hadron properties [1, 2,3]. Even if the changes in quark condensates are small, the absolute difference between the in-medium and bare masses of hadrons is expected [3,4] to be larger for heavier hadrons.

The charmed mesons, which consist of light $q,\bar{q}$ and heavy $c,\bar{c}$ quarks, are considered suitable probes of in-medium modification of hadron properties. Similaly to $\bar{K}$ $(\bar{q}s)$ and K $(q\bar{s})$ mesons, the D $(\bar{q}c)$ and $\bar{D}$ $(q\bar{c})$ satisfy different dispersion relations in matter because of the different sign of q and $\bar{q}$ vector couplings [3]. While the D meson mass is reduced in nuclear matter, the $\bar{D}$ mass is raised, as is illustrated by Fig.1a). Calculations with the Quark Meson Coupling model (QMC) [5] show that already at normal nuclear density ρ_0 the mass splitting between D and $\bar{D}$ mesons is about 160 MeV.

It was proposed [4] that the modification of the D meson in nuclear matter can be identified by enhanced subthreshold production of open charm in $\bar{p}A$ annihilation. Because of charm conservation, D and $\bar{D}$ mesons are produced pairwise. As is shown in Fig.1b) the sum of D and $\bar{D}$ masses depends substantially on nuclear density. The downward shift of the $D\bar{D}$ threshold at ρ_0 is $\simeq$−100 MeV. A QCD sum rule estimate [6] predicts about the same shift.

Furthermore, an attractive D-nucleus potential can be measured by investigating charmed mesic nuclei [3]. The reduction of D mass in matter might affect open charm production [7] and J/Ψ suppression [8] in relativistic heavy ion collisions.

In contrast to open charm, charmonium mesons consist of heavy $c\bar{c}$ quarks and can be affected only by gluonic condensates. It was expected that the modification of properties of heavy quarkonia in matter would be almost negligible [9]. In that case, the overall $D\bar{D}$ mass at some nuclear density might cross the masses of excited charmonium states, as is illustrated by Fig.1b).

The crossing of the charmonium states levels and the $D\bar{D}$ threshold in nuclear medium might result in the melting [10] of excited charmonium mesons.

Here we investigate the modification of widths of charmonium states at finite nuclear density with D and $\bar{D}$ in-medium masses predicted by QMC [3]. We consider simultaneous modification of both D and $\bar{D}$ mesons, as is illustrated in Fig.1 and study $\Psi''(3770)$, $\Psi'(3686)$ and χ_{c2} decay into $D\bar{D}$ in nuclear matter. The χ_{c0} modification is not discussed since the $D\bar{D}$ threshold does not cross its

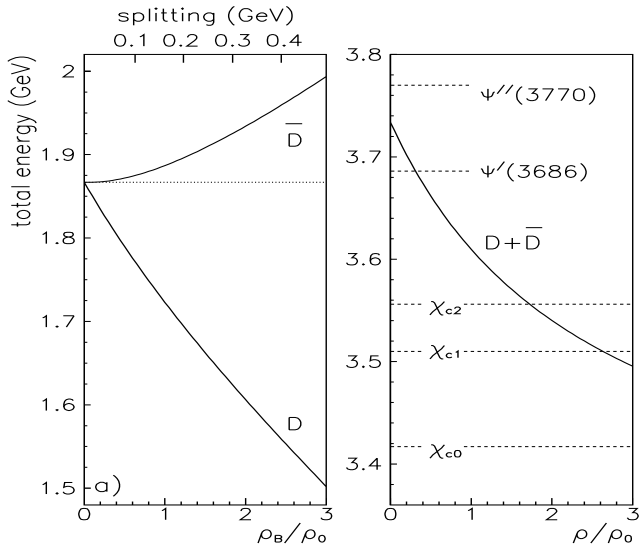

Fig. 1. a) The in-medium mass of D and $\bar{D}$ mesons as a function of nuclear density ρ/ρ_0, with ρ_0=0.16 fm^{-3} and the $D\bar{D}$ mass splitting (upper axis). b) The solid line shows overall $D\bar{D}$ mass as a function of density. The dashed lines indicate the masses of excited charmonia.

mass even at $\rho=3\rho_0$, as is shown in Fig.1. The $\chi_{c1}\to D\bar{D}$ decay is suppressed by parity conservation.

2 Ψ''(3770).

The Ψ'' charmonium lies above the $D\bar{D}$ threshold in free space and its dominant decay width into $D\bar{D}$ channel is given by

$$\Gamma_{\Psi''\to D\bar{D}}=\frac{g^2_{\Psi''D\bar{D}}}{3\pi}\frac{q^3}{m^2_{\Psi}}, \tag{1}$$

where m_Ψ is the $\Psi''(3770)$ mass and q is the D meson momentum in the charmonium rest frame,

$$q=\frac{[(m^2_{\psi}-m^2_D-m^2_{\bar{D}})^2-4m^2_D m^2_{\bar{D}}]^{1/2}}{2m_\Psi}, \tag{2}$$

with m_D and $m_{\bar{D}}$ the masses of D and $\bar{D}$ mesons, respectively, while the coupling constant $g_{\Psi''D\bar{D}}$=14.89 is fixed by the vacuum decay width $\Gamma_{\Psi''\to D\bar{D}}$=23.6 MeV.

If $\Psi''D\bar{D}$ coupling does not change in matter the modification of the $\Psi(3770)$ width is entirely given by D and $\bar{D}$ in-medium masses and is determined by the phase space dependence of the charmonium decay width. In that case the in-medium $\Psi(3770)$ width depends substantially on nuclear matter density, as is shown by the solid line in Fig.2a).

Within the $^3P_0$ model [11] the $\Psi''D\bar{D}$ coupling itself depends on the D and $\bar{D}$ masses via

$$g^2_{\Psi''D\bar{D}}=\frac{\pi^{3/2}\,2^{11}\,\gamma^2 m_\Psi}{5\,\beta^7\,3^{10}}\,[(q^2+m^2_D)(q^2+m^2_{\bar{D}})]^{1/2} \times(15\beta^2-2q^2)^2\,\exp{(-q^2/6\beta^2)}, \tag{3}$$

where the oscillator length scale β=360 MeV is fixed by light mesons decays [11], while the interaction strength γ=0.33 is determined by $\Psi''\to D\bar{D}$ decay.

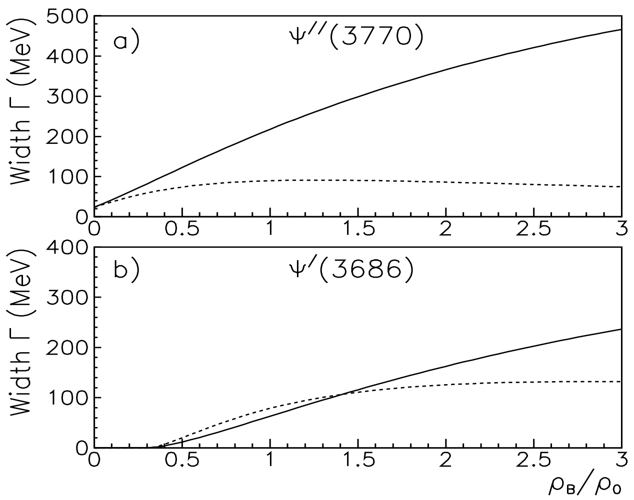

Fig. 2. Decay widths of Ψ''(3770) a) and Ψ'(3686) b) charmonium states into $D\bar{D}$ as a function of nuclear matter density in units of ρ_0 . The solid lines show the phase space dependence, while the dashed lines are the results from the $^3P_0$ model. In both calculations the D and $\bar{D}$ in-medium masses are given by the QMC model.

Finally, the dashed line in Fig.2 shows the dependence of the $\Psi''\to D\bar{D}$ decay width on nuclear matter density resulting from the $^3P_0$ model. At normal nuclear density ρ_0= 0.16 fm^{-3} the $\Psi''(3770)$ in-medium width almost saturates $\Gamma_{\Psi''\to D\bar{D}}\simeq$90 MeV, which is $\simeq$3.8 times larger than in vacuum. Furthermore, the $^3P_0$ result substantially differs from the phase space estimate.

The Ψ'' modification in nuclear matter might be studied by dilepton spectroscopy from AA as well as $\bar{p}A$ interactions, since the effect is measurable already at normal nuclear densities. The $\Psi''(3770)$ charmonium does not decay into J/Ψ and thus its modification in matter can not be considered as an additional source of J/Ψ suppression in heavy ion collisions.

3 Ψ'(3686).

The Ψ' charmonium lies below the $D\bar{D}$ threshold in free space, but the $D\bar{D}$ decay channel becomes open at nuclear density $\rho\simeq$0.05 fm^{-3}, as illustrated by Fig.1. The Ψ' is narrow, its total width is 0.277 MeV and partial decay into J/Ψ accounts for $\simeq$54% of the total width.

Although, the $\Psi(3686)$ coupling to $D\bar{D}$ is not directly accessible, it can be estimated within the framework of Vector Meson Dominance model as

$$g^2_{\Psi'D\bar{D}}=\frac{16\pi\alpha^2}{27}\frac{m_\Psi}{\Gamma_{\Psi'\to e^+e^-}}, \tag{4}$$

where α is the fine structure constant, m_Ψ is the $\Psi'(3686)$ mass and $\Gamma_{\Psi'\to e^+e^-}$=2.35 KeV is the radiative $\Psi'\to e^+e^-$ decay width. Finally, the $\Psi'D\bar{D}$ coupling constant is 12.84; the $\Psi''D\bar{D}$ coupling from VMD is to 19.94, which is close to the result from direct $\Psi''\to D\bar{D}$ decay given by Eq.1.

The phase space dependence of the Ψ' in-medium width from Eq.1 is shown by the solid line in Fig.2b). This result again can be compared with the prediction of the $^3P_0$ model given by [11]

$$\Gamma_{\Psi'\to D\bar{D}}=\frac{\pi^{1/2}\,2^9\,\gamma^2}{m_\Psi\,\beta^7\,3^{11}}\,[(q^2+m^2_D)(q^2+m^2_{\bar{D}})]^{1/2} \times q^3\,(15\beta^2-2q^2)^2\,\exp{(-q^2/6\beta^2)} \tag{5}$$

and shown by the dashed line in Fig.2b). Here the calculations were done with parameters β and γ evaluated above. Note that at nuclear densities $\rho\lesssim1.5\rho_0$ both the $^3P_0$ model and VMD phase space estimates are in reasonable agreement. An exciting observation is that at normal nuclear density ρ_0=0.16 fm^{-3} the Ψ' width is $\simeq$70 MeV, which is $\simeq$250 times larger than that in vacuum.

Again, the Ψ' modification in nuclear matter can be measured through dilepton spectroscopy. As we found, the dilepton spectrum from $\Psi'(3686)$ decay in matter might strongly overlap with $\Psi''(3770)$ charmonium decay. Fig.3a) shows dilepton spectra from Ψ' and Ψ'' decays unfolded from the production cross section. The solid lines show the results for matter at normal nuclear density, while the dashed lines indicate the spectra in free space. The measurement of a broad peak around Ψ' pole might be considered as an direct indication of in-medium modification of charmonia.

On the other hand, a large $D\bar{D}$ component of Ψ' charmonium should result in strong Ψ' absorption in nuclear matter, similar to that found [8] for J/Ψ dissociation. Moreover, Ψ' melting in nuclear matter will additionally suppress $\Psi' \to J/\Psi$ decay and partially eliminate J/Ψ yield in heavy ion collisions.

4 χ_{c2}(3556).

The χ_{c2} charmonium level crosses the $D\bar{D}$ threshold at a nuclear density of about 0.28 fm^{-3}. In vacuum the χ_{c2} width is 2 MeV and partial decay into the J/Ψ is $\simeq$13.5%. There is no reliable way to estimate $\chi_{c2}D\bar{D}$ coupling and to evaluate the phase space dependence of the χ_{c2} in-medium width.

In the $^3P_0$ model the $\chi_{c2} \to D\bar{D}$ width is given as [11]

$$\Gamma_{\chi_{c2}\to D\bar{D}} = \frac{\pi^{1/2}\, 2^{12}\, \gamma^2}{5\, m_\chi\, \beta^5\, 3^8}\, [(q^2+m_D^2)(q^2+m_{\bar{D}}^2)]^{1/2} \times q^5\, \exp\left(-q^2/6\beta^2\right), \qquad (6)$$

where m_χ is the χ_{c2} mass and parameters β and γ are listed above. The in-medium χ_{c2} width is shown in Fig.3b) as a function of nuclear matter density. The χ_{c2} modification becomes significant only at large densities.

5 Conclusion.

Modification of the D and $\bar{D}$ meson masses in nuclear matter leads to a substantial increase of the χ_{c2}, Ψ' and Ψ'' decay widths into the $D\bar{D}$ channel.

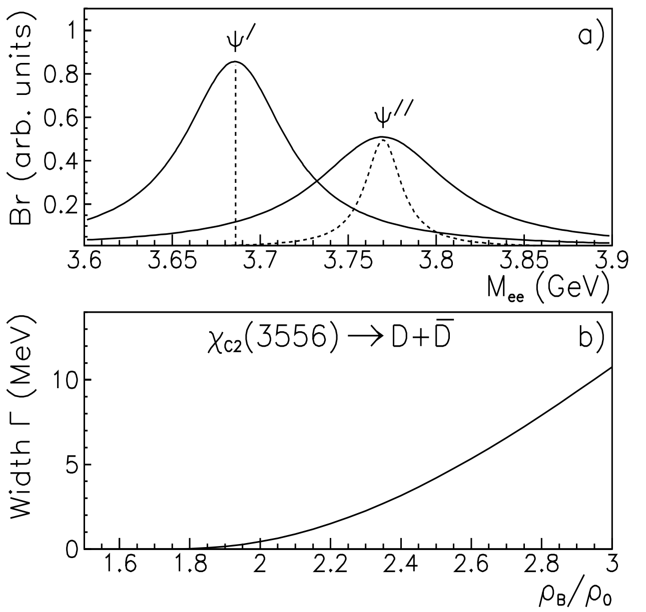

Fig. 3. a) Dilepton spectra from Ψ' and Ψ'' decays at normal nuclear density ρ=ρ_0=0.16 fm^{-3} (solid lines) and in vacuum (dashed lines). b) Decay width of χ_{c2}(3556) charmonium into $D\bar{D}$ as a function of nuclear matter density in units of ρ_0 predicted by the $^3P_0$ model with D and $\bar{D}$ in-medium masses given by QMC.

The calculations with the density independent coupling constants between the Ψ' and Ψ'' charmonium and $D\bar{D}$ pair results in strong and monotonic density dependence of the Ψ' and Ψ'' in-medium widths due to increase of the final state phase space. Within the $^3P_0$ model these couplings are also considered as a function of the in-medium D and $\bar{D}$ masses and as a result the Ψ' and Ψ'' charmonium widths do not increase monotonically with nuclear density, but saturate at ρ_0=0.16 fm^{-3}. It was found that the saturation limits are $\Gamma_{\Psi'\to D\bar{D}} \simeq$70 MeV and $\Gamma_{\Psi''\to D\bar{D}} \simeq$90 MeV, which can be compared with vacuum widths of 0.277 MeV and 23.6 MeV, respectively.

The χ_{c2} charmonium level crosses the $D\bar{D}$ threshold at $\rho \simeq$ 1.25ρ_0 and its width increases with nuclear matter density. At $\rho \simeq 3\rho_0$ the χ_{c2} decay width into $D\bar{D}$ is about 11 MeV, which may be compared with total $\Gamma_{\chi_{c2}}$=2 MeV width in vacuum.

We conclude that modification of the D and $\bar{D}$ in matter most dramatically affects the Ψ' charmonium. This can be detected by dilepton spectroscopy as the appearance of a broad peak near the Ψ' pole or as anomalous Ψ' suppression in nuclear matter.

Our results are in agreement with the most recent findings [12] that both the mass and width of Ψ''(3770) depend significantly on the D meson mass.

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